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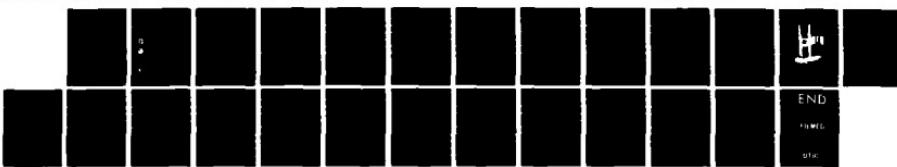
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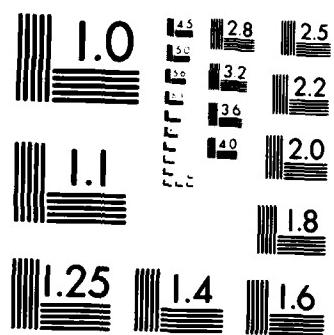
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Rain Rate Determinations From Electronic Weight Measurements: Instrument Description and Data Reduction Techniques

ROBERT O. BERTHEL
ANTHONY J. MATTHEWS



9 August 1984



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ATMOSPHERIC SCIENCES DIVISION
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The Air Force Geophysics Laboratory has designed and constructed a prototype instrument for the derivation of rain rate from electronic measurements of collected water. This device gives 30-s averaged-rate-values every 3 s and produces rain rate records that show a detailed structure of the rainfall variability. Since this measuring concept does not require a particular weight or volume of collected water before a reading, it is a considerable improvement over the rain measuring instruments currently in general use.			
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Electronic Weight Measurements: Instrument Description and Data Reduction Techniques

19. Abstract (Contd)

This report describes the prototype instrument and specifies the data reduction techniques that have been devised for this particular rain-measuring concept. The information contained ~~within~~ should enable others to construct similar devices and avoid some of the problems that plagued our initial efforts. Consideration of the recommendations made in this report may result in more efficient instruments and/or better methods of data reduction.

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Preface

The authors wish to express their appreciation to the individuals responsible for the original design and operation of the prototype rain rate meter; Vernon G. Plank, MSgt Stephen Crist (retired) and TSgt Dennis L. LaGross. Thanks are also extended to the AFGL machine and sheetmetal shops for the construction. A special thanks to Carolyn Fadden for typing this manuscript.

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Rain Rate Determinations From Electronic Weight Measurements: Instrument Description and Data Reduction Techniques

I. INTRODUCTION

In 1981, the Air Force Geophysics Laboratory (AFGL) initiated a study of the characteristics of naturally falling snow using instruments¹ specifically designed and built for that purpose. One of these devices, the snow rate meter, utilized an electronic balance to measure the weight of the snowfall for the determination of snow rate. Subsequent measurements taken during the SNOW-ONE field experiments resulted in snow-rate records that detailed the fine structure of the snowfall, and agreed with other data acquired from attenuation studies.²

It was a logical step to apply this concept to the measurement of rainfall. Initial feasibility studies were conducted using a Belfort rain gauge, with the tipping bucket mechanism replaced by an electronic balance,³ while a new prototype instrument was being constructed.

(Received for publication 9 August 1984)

1. Gibbons, L. C., Matthews, A. J., Berthel, R.O., and Plank, V. G. (1983) Snow Characterization Instruments, AFGL-TR-83-0063, AD A131984.
2. Berthel, R.O., Plank, V.G., and Main, B.A. (1983) SNOW-ONE-A and B Characterization Measurements and Data Analysis, AFGL-TR-83-0856, AD A141245.
3. Plank, V.G., and Berthel, R.O. (1983) High Resolution Snow and Rain Rate Measurements, Reprints of the Fifth Symposium on Meteorological Observation and Instrumentation, AFGL-TR-83-0107, AD A128296.

This report describes the prototype instrument and the novel features that are unique to this measuring device. The problems associated with data acquisition and reduction are explained, and solutions currently being employed to overcome these problems are detailed. The value of rain rate measurements derived from using this instrument is discussed together with suggestions for improving instrument design and operation.

2. INSTRUMENT DESCRIPTION

The rain rate meter has five basic components: housing, collector, transfer mechanism, accumulator, and electronic balance/recorder as shown in the diagram of Figure 1 and photograph in Figure 2. Dimensions listed herein are those of the prototype instrument and are only included for general information. No claim is made that these specifications are critical or, in fact, optimum. A patent application has been filed on the basic design of this device.

2.1 Housing

The instrument housing is essentially a 1 m aluminum cylinder with an outside diameter of 36 cm and wall thickness of 1.6 mm (1/16 in.). Three steel legs are attached by two brackets that girdle the cylinder's lower section. These legs are adjustable to level the instrument, and with the legs in place the overall instrument height above ground is ~1.2 m. Three tabs are attached to the upper portion of the cylinder for guide wires to anchor the instrument to prevent tipping in strong winds. A 25.4-cm door is provided for internal access. A flange, positioned directly above the door, prevents wind-driven rain from entering the compartment. A circular, aluminum platform is attached to the inside diameter of the lower part of the cylinder to support the electronic balance and associated mechanism. The platform contains a drain hole to dispose water after measurements have been taken.

2.2 Collector

The collector is a 35-cm aluminum funnel with a 30-degree cone angle. The top of the funnel is attached to the inside of the cylinder housing 9 cm below the rim. Thus, the funnel diameter is identical to the cylinder's inside diameter (35.68 cm), which is a deliberate dimension to give a convenient 1000-cm^2 collection area. A 10-mm ID tube, 10 mm in length, serves as the exit port at the apex of the cone.

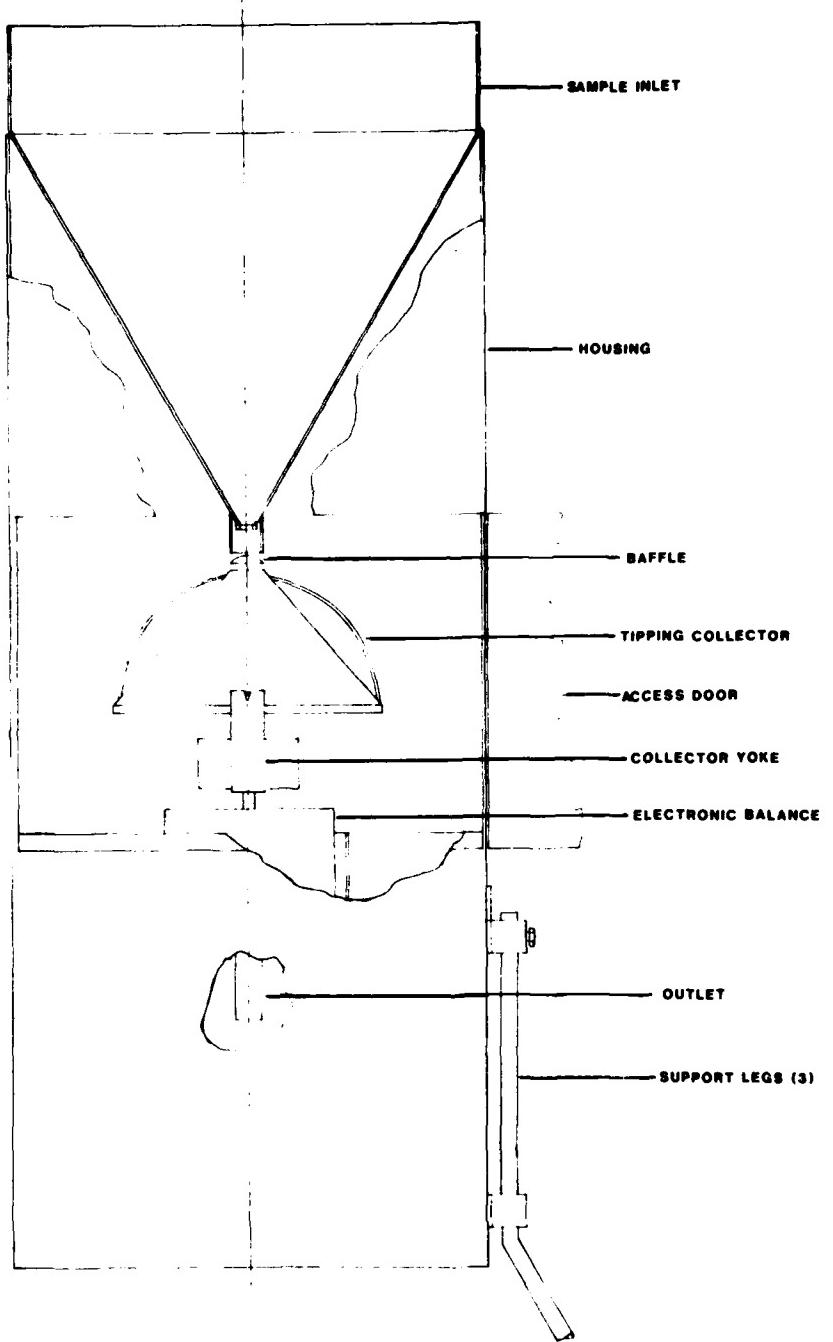


Figure 1. Diagram of Rain Rate Meter

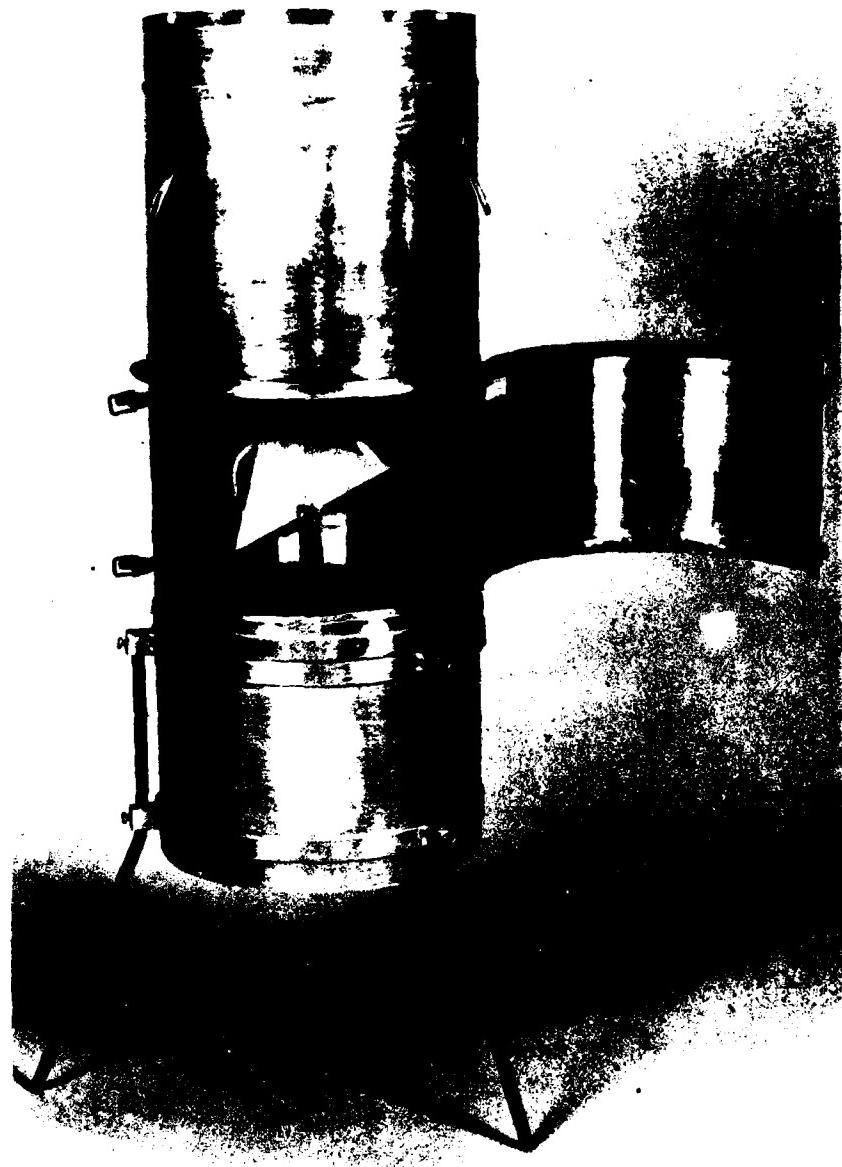


Figure 2. Photograph of Prototype Rain Rate Meter

2.3 Transfer Mechanism

Because of the sensitivity of the electronic balance, care must be taken that the water flowing from the funnel collector does not directly impact the weighing mechanism. The momentum of the falling water can cause erratic weight recordings, thus a smooth transfer from collector to weighing bucket is required. This is accomplished by suspending a circular disk or baffle from the exit tube to break the downward momentum of the collected water. Plastic foam material, mounted on the top of the sample accumulator, is positioned directly beneath, and as close as possible without contact to the disk. Water leaving the disk flows directly onto and through the foam into the accumulator or weighing bucket. The water is essentially being weighed immediately upon exiting the disk. Since it is not allowed to drop into the accumulator, a smooth transfer results.

2.4 Accumulator

The sample accumulator is an aluminum, dual-compartmented device that pivots on a shaft inserted in place of the shaft that supports the weighing pan on the electronic balance. The details of this mechanism are shown in Figure 3. Each compartment has a 150-ml capacity at which time it tips and spills its contents while moving its twin into the collection position. A block of plastic foam is positioned to dampen or cushion its movement. As mentioned in 2.3, plastic foam covers the top of each section to insure the orderly transfer of water.

2.5 Electronic Balance/Recorder

A Scientech, model 3340 electronic balance, having 0.01-g resolution with a 1000-g maximum, is used to measure the weight of the collected water. The balance has a remote sensing head with ~ 45.7 m (150 ft) of low capacitance cable that allows the instrument to be exposed to unobstructed rainfall. A timing circuit has been incorporated to insure accurate 3-s sequential weight readings. Data is recorded on magnetic tape with a Tektronix, model 4923 digital recorder, for subsequent computer processing.

3. DATA REDUCTION

Although named a rain rate meter, the instrument just described is actually a device that is capable of recording the mass of water falling on a given surface area over a specific amount of time. As such, it is a provider of time-resolved weight measurements from which rate is derived.

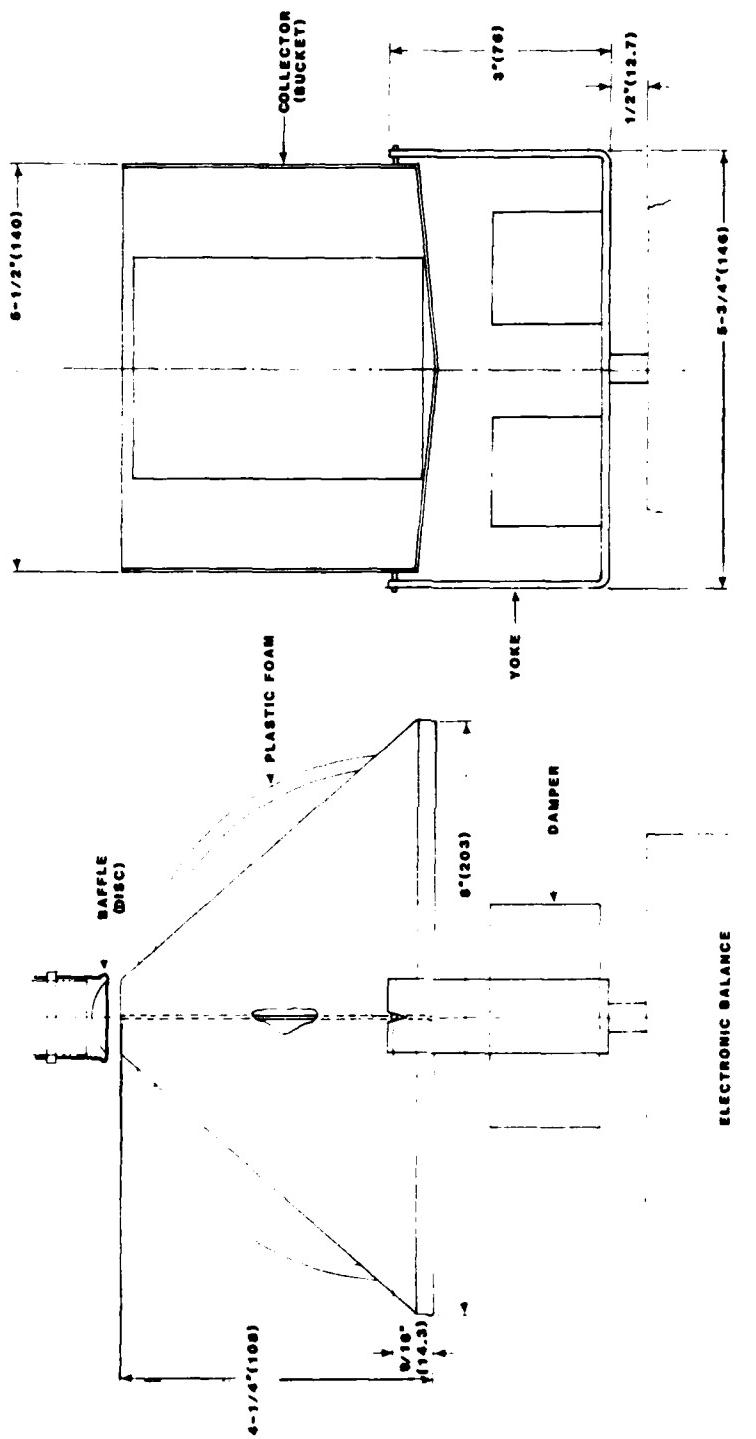


Figure 3. Tipping Bucket Detail

Since weight readings are the sole output from the electronic balance, the time that the instrument is made operational has to be recorded separately. Subsequent times of individual weight readings are determined by the summation of the basic time increments (3 s) to the initial start time.

During periods of rain, the raw-weight data from the balance will show increasing weights with each successive time increment. A repetition of a particular weight indicates the absence of rainfall.

There are however, several definable exceptions to these ground rules that can be recognized and corrected by computer operation. When the tipping bucket fills to capacity and empties by dumping its contents, there is a sharp decrease in weight. During periods of no apparent rain and repeating weight readings, an occasional variance of 0.01 g (basic resolution of the balance) is sometimes encountered as the result of electronic noise or ambient temperature change. Under conditions of very light rainfall, the weight readings exhibit increases, separated by periods indicating "no rain" conditions. Adjustments are made in the raw-weights to correct the deficiencies caused by these exceptions, and the resulting smoothed-weight data are used in the determination of rain rates.

3.1 Weight Smoothing

The first adjustment made to the raw-weight data is the correction of weight decreases. The section of the computer program that controls this process is termed the *summation routine*. Its objective is to produce weight data that shows continuously rising weights during periods of rain.

When the tipping bucket dumps, the raw-weight readings exhibit a sudden decrease to an approximate zero-value before increase resumes. The effects of the actual voiding of water from the bucket takes place within 2 or 3 time increments (6 to 9 s) depending upon where during the first time increment the event was initiated. A period of instability lasting one or two time increments (3 to 6 s) follows, before weight readings begin increasing in a normal manner. The instability can be attributed to vibration caused by the tipping bucket movement and/or by residual water drops in the final stages of emptying the bucket.

To overcome this problem, the upward trend of weight data immediately preceding the dump is extrapolated to span the region of the weight curve that incorporates the dump and instability period (Figure 4). Since the maximum time for the readings to regain stability is five time increments (15 s), this period is used to define the time the trend is derived.

The weight differences or delta weight (Δw) over the five time increments immediately preceding the tipping bucket dump, are averaged to determine the trend. If the plotted weight points are numbered, as shown in Figure 4, with 0

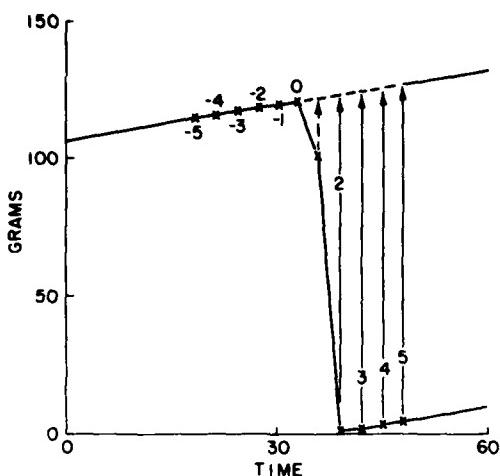


Figure 4. Weight-Time Plot Showing Tipping Bucket Dump and the Extrapolation Procedure used to Adjust the Weights

assigned to the last point before evidence of the tipping bucket dump, the weight points considered in the calculation of trend are numbered -1 through -5. Conversely, the points in the extrapolation are numbered 1 through 5. The average delta weight is then found by the equation

$$\overline{\Delta w} = \frac{\sum_{n=0}^{n=-4} w_n - w_{n-1}}{5} g , \quad (1)$$

where the extrapolated values are determined by

$$w_n = w_0 + n \overline{\Delta w} \quad g. \quad (2)$$

All subsequent positive Δw are then added to the preceding weight to produce continuously rising data.

Although this routine was specifically designed to adjust the weight data for tipping bucket dumps, it can be generally applied to correct any negative Δw values such as those caused by electrical noise or sudden temperature variations.

3.2 Weight Peak Connection

As previously mentioned, the weight data should always show an increase with time during periods of rain. However, in very light rain conditions

($< \sim 1 \text{ mm hr}^{-1}$) the sizes of the prevailing drops are small, or there are only a few large-sized drops in evidence. In either case, there is not enough water present to thoroughly wet the surface of the collector, and drops adhere to the sides because of surface tension. Upon reaching a critical mass, water will move downward over the collector surface towards the exit port engulfing other adhered drops along the way. The entity resulting from this collection process that finally enters the weighing bucket commonly gives weight increases of ~ 0.05 to ~ 0.2 g, depending upon its origin on the collector surface. The increase is followed by a period of no weight change, until the collection process is repeated. The time between increases is inversely proportional to the amount of rainfall; thus smaller rates give longer times, and rates approaching $\sim 1 \text{ mm hr}^{-1}$ have occasional short periods of repeating weights (Figures 5 and 6).

It is very apparent that the time-sequence of repetitious weights in very light rain conditions are not periods where rain has ceased falling. They exist only because of the inefficiency of the instrument's collection and transfer system. This particular instrument has a lower rain rate limit of $\sim 1 \text{ mm hr}^{-1}$, where lesser rates can not be analyzed in a normal manner.

If, in fact, a very light rain exists, a logical assumption is that the raw-weight data should show slight weight increases in each 3-s reading. This can be approximated by a straight-line interpolation between the separated weight readings, or weight peak connection, and the assigning of approximate weight values to each of the intervening time increments. This interpolation is shown by the dashed lines in Figures 5 and 6.

Occasional increases of less than 0.05 g are evident in the weight data, almost always occurring in conjunction with increases associated with a collection of drops, either immediately before or directly afterwards, as shown in the weight step at ~ 2007 in Figure 5. They are, most probably, an effect of the water dripping from the striker plate onto the foam transfer mechanism, and as such, are treated as part of the increase caused by the collection process.

Another problem arises with the use of the peak connection routine, that being the instructions programmed into the computer so it may recognize actual periods where rain was nonexistent. A 5-min time limit was arbitrarily established to define a period of possible rain. If no weight increase is observed within the 5-min limit, the repeating weights are left unaltered giving a rain rate of zero throughout the period. If any weight increase is observed in less than 5-min, the interpolation process will assign a calculated weight for each 3-s interval, thus establishing a uniform rate for the period. For example, if a weight increase of

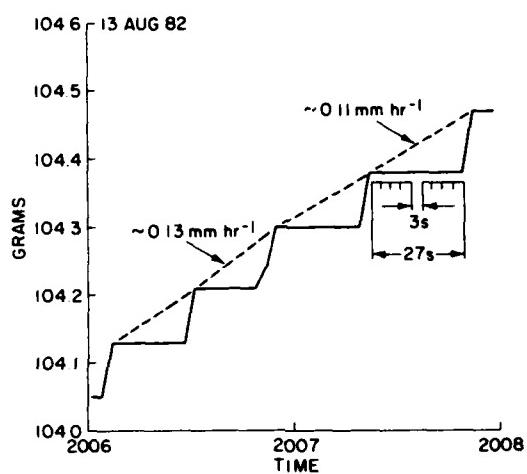


Figure 5. Weight-Time Plot of Very Light Rainfall (0.1 to 0.14 mm hr^{-1}) and the Interpolation Procedure Used to Adjust the Weights

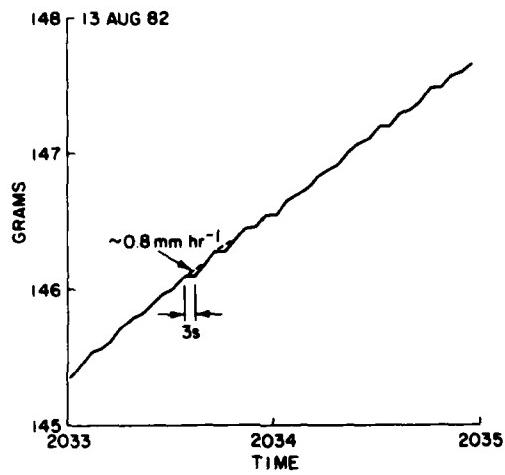


Figure 6. Weight-Time Plot of Light Rainfall (0.8 mm hr^{-1}) and the Interpolation Procedure Used to Adjust the Weights

0.05 g was evident in 5 min (the approximate smallest weight attained by the collection process) the rain rate would be 0.006 mm hr^{-1} . The rate corresponding to one drop of $\sim 0.2 \text{ g}$ collected over 5 min would be $\sim 0.024 \text{ mm hr}^{-1}$. Hence these are lower limits due to our data reduction process.

3.3 Rain Rate Calculation

Rain rate is the amount of water that accumulates on a surface in a given unit of time and is usually normalized to be expressed in millimeters or inches per hour. With knowledge of the weight of accumulated water, it can be calculated as

$$R = \frac{\Delta w c}{A t} \text{ mm hr}^{-1}, \quad (3)$$

where Δw is the weight in grams of water that fell on the surface A (mm^2), in time t (hr), and $c = 1000 \text{ mm}^3 \text{ g}^{-1}$.

Using the smoothed weight data, rain rate can be calculated from the weight differences between readings in the basic time increments of 3 s or $1/1200 \text{ hr}$. When derived in this manner, the resulting rain rates are nothing more than magnified Δw readings and are shown as the solid lines in Figures 7 and 8 for the same time periods as the weights plots of Figures 5 and 6. The horizontal portions of these plots represent two or more time periods having the same Δw such as those resulting from interpolation.

Since the weight readings are in 3-s increments, it is not surprising to observe the abrupt, erratic rate changes evidenced in these figures. Although these plots are truly representative of the 3-s smoothed-weight data, it is illogical to believe that rain rate will change in a precise 3-s time sequence. This indicates that some degree of averaging has to be applied to dampen the fluctuations of these data.

Initial averaging efforts involved separating the data into three distinct ranges of rain rates and applying different analytical routines to each. That complicated analysis has since been replaced with an averaging technique that can be applied to all the data. This is accomplished by using weight differences over longer periods of time as

$$R = \frac{[w(0+\eta) - w(0-\eta)] c}{A \eta / 600} \text{ mm hr}^{-1}, \quad (4)$$

where Δw is now the difference between the weight values η time-increments ahead and behind the reading w_0 . The time of the averaging increment is now

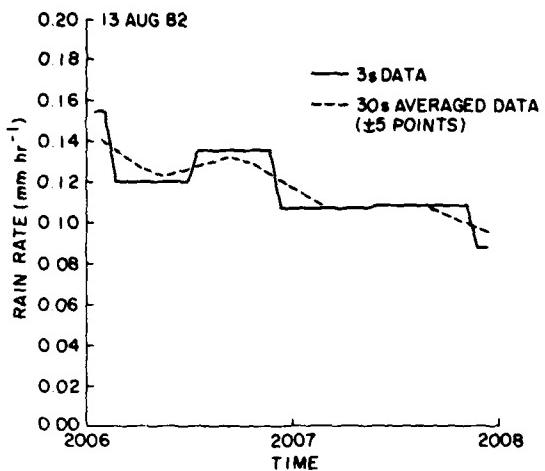


Figure 7. Rain Rates Derived from the Weight Data of Figure 5

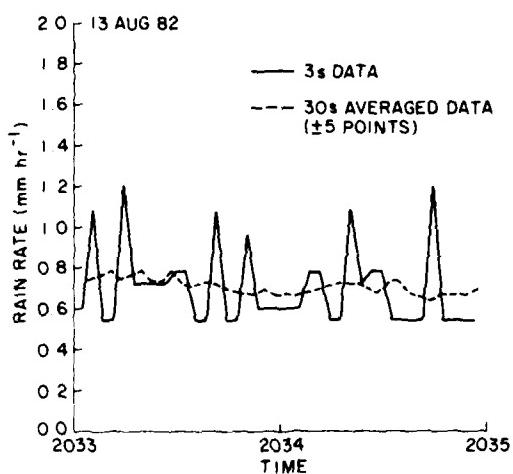


Figure 8. Rain Rates Derived from the Weight Data of Figure 6

$2\eta \times 3 \text{ s} / 3600 \text{ s hr}^{-1}$ or $\eta / 600 \text{ hr}$. The smoothed-weight data averaged over 10 time increments (± 5 points or 30 s) are shown as dashed lines in Figures 7 and 8.

As expected, rain rates display different degrees of suppression as averaging increases. Definition of averaging periods has always posed problems in data analysis, since too much averaging can severely mask data characteristics. Thus, the most ideal amount of averaging will dampen the noise of the data yet retain individual characteristic variations. One method of making a value judgement on averaging period is to observe the changes in variability with increases in averaging time. The point at which the suppression in data variation shows small, relatively-constant changes with each step increase in averaging, is considered the optimum averaging interval.

Standard deviation is the basic measurement of variation or dispersion in a data set. If comparisons are to be made between data sets, a more relative measure has to be used,⁴ that is, the coefficient of variation or the expression of the percentage of standard deviation relative to the mean. It is calculated as

$$V = \frac{100 \sigma}{\bar{R}} , \quad (5)$$

where σ is the standard deviation and \bar{R} is the mean rain-rate for a particular set of data.

An analysis was conducted on the coefficients of variation that were determined by averaging periods with up to ± 10 time increments (60 s), from 22 rain events, taken over four days. An event was defined as a 1-hr period of continuous rain, or a lesser time in showery situations, where the rainfall was above a trace (0.1 mm hr^{-1} or $\sim 0.005 \text{ in. hr}^{-1}$). These coefficients varied in absolute values depending upon the particular rainfall in each event. Since the objective was to derive a general averaging period, the coefficients from each were combined to form mean values, shown plotted as crosses connected by a solid line in Figure 9. The dotted lines represent \pm one standard deviation in these coefficients, and are included to give an indication as to the variability inherent in the 22 events. The dashed line is the straight-line extrapolation from the last five averaging intervals, namely ± 6 through 10 points. The point of departure of the dashed from the solid line is the $\sim \pm 5$ time-interval (30 s). Hence, that averaging value was chosen as the most optimum for the particular instrument previously described.

4. Wessel, R.H., and Willet, E.R., (1963) Statistics as Applied to Economics and Business, Holt, Rinehart and Winston, N.Y.

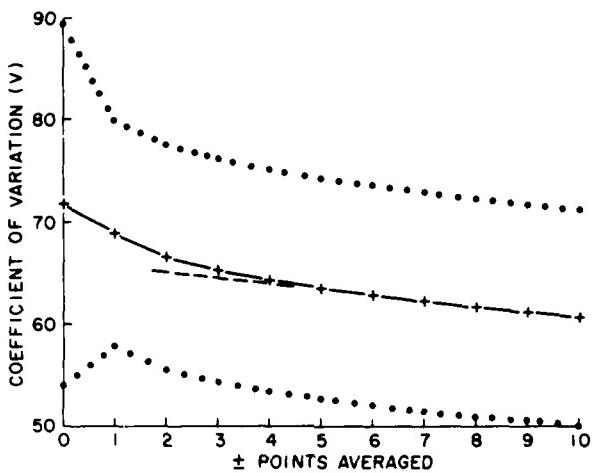


Figure 9. Coefficient of Variation Data Used to Determine Averaging Period for Rain Rate Calculations

This departure point is more obvious when the differences between the coefficient of variation values (ΔV) are plotted vs the midaveraging points as in Figure 10. The small, relatively-constant changes in V , referred to earlier, are indicated by the dashed line.

4. CONCLUSIONS AND RECOMMENDATIONS

Graphic presentations of rates derived from the electronic measurements of rainfall weights and processed in the manner described in the preceding sections, display fine-structured character that delineates the variability present in rain situations. A typical 1 hr of data acquired at Hanscom Air Force Base (HAFB) on 1 Sep 82 is shown in Figure 11 as an example.

At this time no measurements have been taken in concert with attenuation studies, although an investigation of this nature is planned for the near future. Based on previous experiences with snowfall measurements, it is expected that rain rates and electromagnetic attenuation will correlate well. This type of instrument may provide the means to evaluate and/or calibrate systems whose efficiencies are dependent upon rain intensities.

The short-term variabilities in rain shown in Figure 11 are not unique and are evident in the majority of data recorded thus far. They do however, indicate

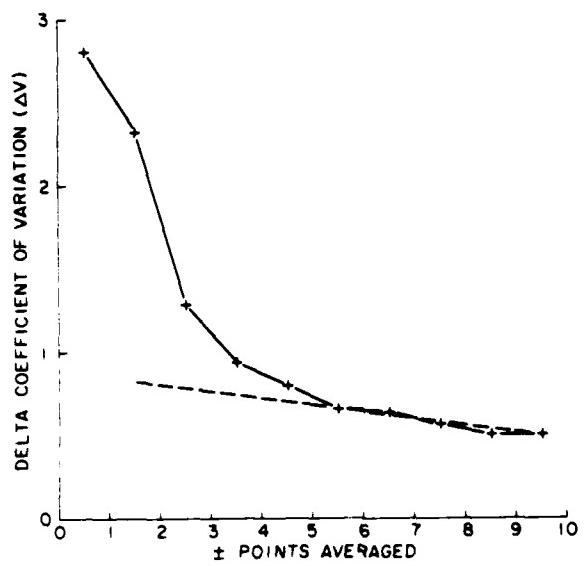


Figure 10. Differences in Coefficient of Variation with Averaging

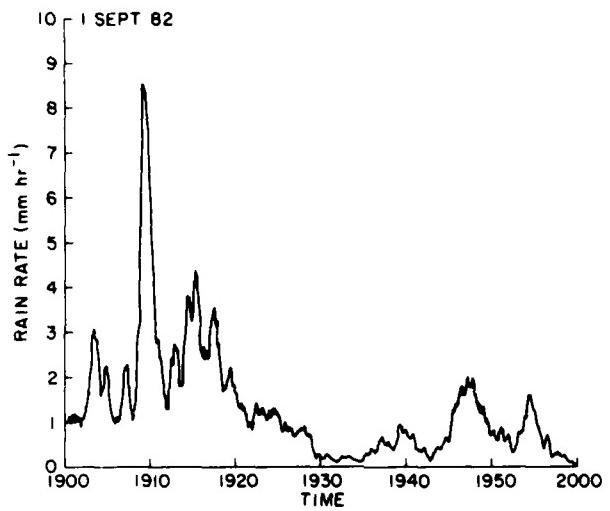


Figure 11. Example of Typical Rain Rate Data from Weight Measurements Taken on 1 Sep 82 at Hanscom AFB

that substantial uncertainty may exist in any attempt to deduce short-term rates from those taken at longer time periods. Since the weight data from this instrument are stored on magnetic tape, comparisons of short and long-term averaging by computer processing may give an assessment of the possible errors. An investigation of this nature is presently being conducted on data taken at HAFB during 1982 and 1983.

Studies are also being made on a possible prediction scheme of persistence; the time the rate exceeds specific intensity levels. This type analysis could prove useful in system design and/or evaluation, and made area-specific with the application of past climatological data.

Several refinements are currently being considered to improve the instrument's operation. The surface of the collection funnel on the prototype instrument was polished in the mistaken belief that a smooth surface would enhance water flow. The opposite proved to be true with water accumulating in beads during very light rain, as described in Section 3.2. Subsequent tests indicate that the problem of drop accumulation on the collector sides may be alleviated by roughening the surface. The resulting porosity should allow the surface to become wet at the onset of rain and retain the wetness throughout a rainy period.

The buckets of the tipping mechanism should be of larger capacity to give a longer time between dumps. Since 15 s of weight readings are essentially lost on each dump (Section 3.1), it is conceivable that a substantial amount of data may be missed in very heavy rain using the ~ 150-ml capacity of the prototype instrument. Larger buckets of lighter material and/or an electronic balance with a higher maximum weight limit, could solve this problem.

Data averaging may be reduced by decreasing the current 3-s balance-update-time sequence to 1 or 2 s. If the ± 5 time-interval averaging remains applicable with 1-s data, the averaging period would reduce to 10 s.

5. ABBREVIATIONS

A	area
AFGL	Air Force Geophysics Laboratory
c	constant relating volume and weight of water
cm	centimeters
g	grams
HAFB	Hanscom Air Force Base
hr	hour
in.	inch
m	meter
ml	milliliter
mm	millimeter
n	number
R	rain rate
\bar{R}	mean rain rate
s	seconds
SNOW-ONE	Scenario Normalization for Operations in Winter Observation and the National Environment
t	time
V	coefficient of variation
ΔV	difference between coefficients of variation
w	weight in grams
Δw	difference between weights in grams
η	number of weight readings for averaging
σ	standard deviation

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